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Data ingestion into NeQuick 2

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[1] NeQuick 2 is the latest version of the NeQuick ionosphere electron density model developed at the Aeronomy and Radiopropagation Laboratory of the Abdus Salam International Centre for Theoretical Physics (ICTP) - Trieste, Italy with the collaboration of the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria. It is a quick-run model particularly designed for trans-ionospheric propagation applications that has been conceived to reproduce the median behavior of the ionosphere. To provide 3-D specification of the ionosphere electron density for current conditions, different ionosphere electron density retrieval techniques based on the NeQuick adaptation to GPS-derived Total Electron Content (TEC) data and ionosonde measured peak parameters values have been developed. In the present paper the technique based on the ingestion of global vertical TEC map into NeQuick 2 will be validated and an assessment of the capability of the model to reproduce the ionosphere day-to-day variability will also be performed. For this purpose hourly GPS-derived global vertical TEC maps and hourly foF2 values from about 20 ionosondes corresponding to one month in high solar activity and one month in low solar activity period will be used. Furthermore, the first results concerning the ingestion of space-based GPS-derived TEC data will be presented.

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1. Introduction

[2] Empirical models like IRI [*Bilitza*, 2001; *Bilitza and Reinisch*, 2008] and NeQuick [*Hochegger et al.*, 2000; *Nava et al.*, 2008] have been developed as climatological models, able to reproduce the typical median condition of the ionosphere. In order to pass from ionosphere "climate" to "weather" there is a need to have models able to reproduce the current conditions of the ionosphere. Indeed, several assimilation schemes (e.g. Utah State University (USU) Global Assimilation of Ionospheric Measurements (GAIM) [*Schunk et al.*, 2004], Jet Propulsion Laboratory (JPL)/University of Southern California (USC) Global Assimilative Ionospheric Model (GAIM) [*Wang et al.*, 2004], Electron Density Assimilative Model (EDAM) [*Angling and Khattatov*, 2006]) have been developed for this purpose: they are of different complexity and rely on diverse kinds of background models and data. In the case of NeQuick, the needs of simplicity and speed behind the genesis of the model led to the implementation of electron density retrieval techniques relying on the use of "effective" parameters, that are defined on the bases of the model and the experimental data considered. In particular, following the ideas expressed by *Komjathy et al.* [1998] and by *Hernandez-Pajares et al.* [2002], different methods to adapt the NeQuick to vertical TEC maps [*Nava et al.*, 2005] or to ground-based GPS-derived TEC data [*Nava et al.*, 2006] have been developed and their effectiveness has been demonstrated considering the first version of the NeQuick model. In the present paper the ingestion technique based on NeQuick 2 adaptation to global vertical TEC maps will be validated. For this purpose hourly global vertical TEC maps and manually scaled hourly foF2 values from about 20 ionosondes corresponding to one month in high solar activity and one month in low solar activity period will be used. The performance of NeQuick 2 in reconstructing the 3D electron density of the ionosphere will be analyzed in terms of statistical comparisons between experimental and retrieved critical frequencies of the F2 layer. In addition, an assessment of the capability of the model to reproduce the ionosphere day-to-day variability will also be performed by means of a complete analysis concerning the foF2 monthly median values and the inter-decile range of the difference between the experimental and the reconstructed foF2.

[3] Finally, the first results concerning the NeQuick 2 model adaptation to Radio Occultation (RO)-derived TEC measurements will be presented.

2. Data Ingestion Into NeQuick 2

[4] In the present work we consider "data ingestion into NeQuick" to be synonymous with "NeQuick adaptation to a given set of experimental data", where the experimental data are usually GPS-derived TEC and/or ionosonde-derived

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ionospheric peak parameters values. It is understood that the NeQuick adaptation to the ionospheric data is realized to retrieve the 3D specification of the electron density of the ionosphere for the given epochs and the geographic areas where experimental data are available.

[5] Since in the present paper the main effort has been devoted to the validation of the ingestion technique based on the NeQuick 2 model adaptation to the La Plata vertical TEC maps, a brief description of the principal elements involved in the validation will be given.

2.1. The NeQuick 2 Model

[6] The NeQuick 2 [*Nava et al.*, 2008] is an ionospheric electron density model developed at the Aeronomy and Radiopropagation Laboratory of The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria. As indicated by *Nava et al.* [2008], the NeQuick 2 is an evolution of the version 1. Therefore the conceptual structure of the model has remained unchanged. Nevertheless the formulation of some specific parameters has been modified. To describe the electron density of the ionosphere above 90 km and up to the peak of the F2 layer the NeQuick 2 uses a modified DGR profile formulation [*Di Giovanni and Radicella*, 1990], which includes five semi-Epstein layers [*Rawer*, 1982] with modeled thickness parameters [*Radicella and Zhang*, 1995]. Three profile anchor points are used; namely the E layer peak, the F1 peak (if present) and the F2 peak, that are modeled in terms of the "ionosonde parameters" foE, foF1, foF2 and M(3000)F2. These values can be modeled, as indicated by *Leitinger et al.* [2005], or experimentally derived. The model topside is represented by a semi-Epstein layer with a height-dependent thickness parameter [*Hochegger et al.*, 2000] that is empirically determined [*Coïsson et al.*, 2006]. The basic inputs of the NeQuick model are: position, time and solar flux (or sunspot number); the output is the electron concentration at the given location and time. As in the case of the previous version, the NeQuick 2 computer package includes specific routines to evaluate the electron density along any ground to satellite ray-path and the corresponding TEC by numerical integration. The full description of the model, including the complete analytical formulation, can be found in the work of *Nava et al.* [2008].

2.2. The La Plata Ionospheric Model LPIM

[7] The global vertical TEC maps used for the present work, and referred to as La Plata maps, are hourly grids of vertical TEC values with a worldwide distribution and a geographic spacing of 2.5° in latitude and 5° in longitude. These maps, produced by the Satellite Geodesy and Aeronomy (GESA) Group of the National University of La Plata, Argentina, are built from GPS-derived TEC data collected from an average of about 150 International GNSS Service (IGS) stations distributed all over the World (http://igscb.jpl.nasa.gov/). They are based on a spherical harmonic expansion of degree and order 15 for the vertical TEC and the daily solution consists of 24 sets of spherical harmonics coefficients (one for each UT hour) and of one instrumental delay value (known as Differential Code Bias or DCB) for each station and for each satellite. The mapping reference is the Sun-modip [*Azpilicueta et al.*, 2006], where modip is defined as by *Rawer* [1963]. The interested reader is referred to *Brunini et al.* [2004] for a detailed description of the LPIM.

3. Vertical TEC Map Ingestion

[8] As indicated in the Introduction, different methods to adapt the NeQuick to vertical TEC maps [*Nava et al.*, 2005], or to ground-based GPS-derived TEC data [*Nava et al.*, 2006] have been implemented. The general concepts applied to develop electron density retrieval techniques based on the model adaptation to experimental data have also been illustrated by *Nava et al.* [2006].

[9] For completeness, in the next paragraph we summarize the approach that has been used to ingest vertical TEC maps into NeQuick.

3.1. The Vertical TEC Map Ingestion Technique

[10] At a given time, the TEC obtained by integration of the NeQuick electron density profile along a given path is a monotonic function of the 10.7 cm radio flux input. In this context the F10.7 input has therefore to be considered as an effective "ionization level" parameter for the model. Therefore a local and instantaneous effective F10.7 (symbol Az) can be defined as the F10.7 input value that minimizes the difference between an experimental and the corresponding modeled vertical TEC computed by integrating the NeQuick electron density profile. Applying this concept to all vertical TEC values of a global experimental vertical TEC map it is possible to obtain an Az grid that, used as an input for NeQuick, provides a three-dimensional representation of the electron density of the ionosphere all over the World and can therefore be used to retrieve, for example, the relevant foF2 values where needed. By definition, the integration of the retrieved electron density profiles reproduces the starting vertical TEC map with the requested accuracy.

[11] The NeQuick 2 code has been modified, also following *Leitinger et al.* [2001], to use global Az grids (with a spacing of 2.5° in latitude and 5° in longitude) as input in such a way that Az values at any wanted geographic location can be computed by means of interpolation.

3.2. The Vertical TEC Map Ingestion Technique Validation

[12] To validate the procedure described in 3.1 data corresponding to the month of April 2000 and September 2006 have been considered. For each month, 720 hourly La Plata vertical TEC maps have been used for the ingestion and about 12000 manually-scaled hourly foF2 values obtained from about 20 ionosondes have been considered as ground-truth measurements for the validation. In order to visualize their geographical distribution, the location of the ionosondes is shown in Figures 1 and 2. As can be seen from the Space Weather Prediction Center of the National Oceanic and Atmospheric Administration Center (NOAA) Web site (http://www.swpc.noaa.gov/ftpdir/warehouse), these months correspond to a high and a low solar activity period respectively. Considering the geomagnetic activity data as provided by the World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html), it can be reported that the days 6-7-8 of April 2000 were highly disturbed (and a major storm occurred). Therefore the data corresponding to these three days have not been considered in the present

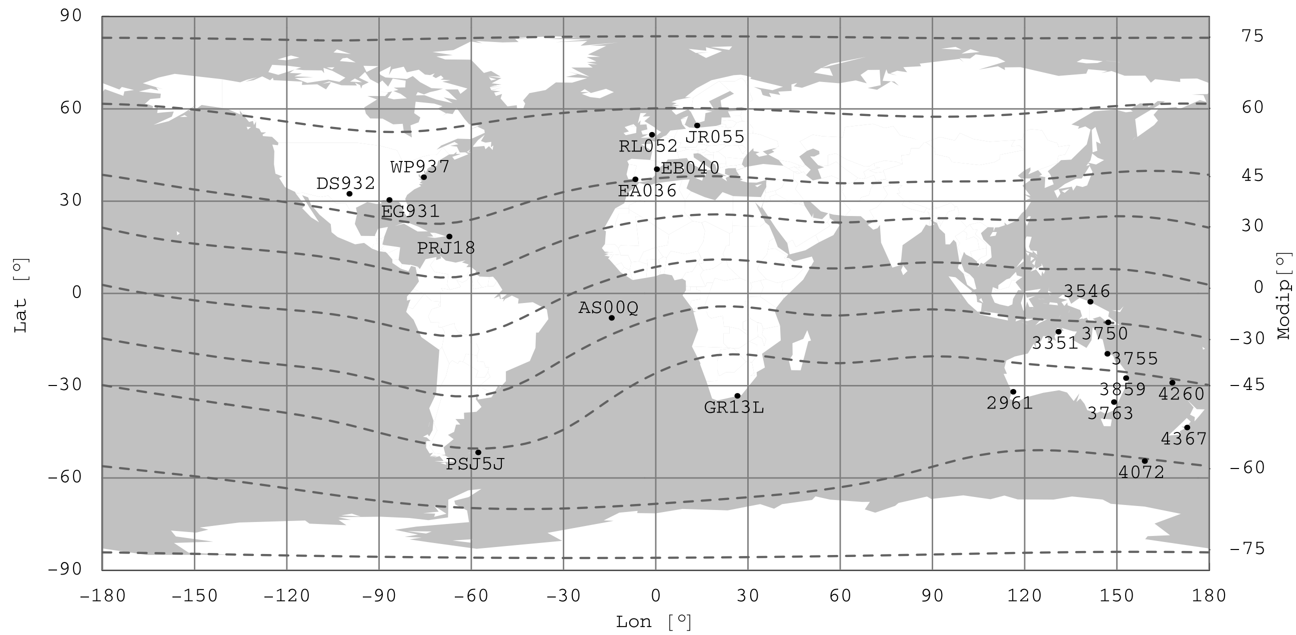

Figure 1. Location of the Ionosondes used for the validation with April 2000 data; modip isolines (dashed) are also indicated.

work. All the remaining days in April were essentially undisturbed and September 2006 was a geomagnetically quiet month. Concerning the validation of the procedure, the following approach has been used.

3.2.1. Using foF2 Data

[13] For each epoch and location where an experimental foF2 value was available, the corresponding NeQuick 2-retrieved value has been computed through the application of the ingestion method described in 3.1. Then, the relative frequency distribution of the difference between experimental and retrieved critical frequencies of the F2 layer (the foF2 error) has been calculated in relation to each month of available data. For comparison purposes the same kind of statistics, based on the same set of experimental data, has been evaluated using the NeQuick 2 model driven by F10.7, the daily 10.7 cm wavelength solar radio flux, and by R12, the smoothed monthly mean Sun Spot Number.

[14] The results concerning the statistics of the differences between experimental and model-derived foF2 data in high solar activity period are shown in Figure 3 (in the case of

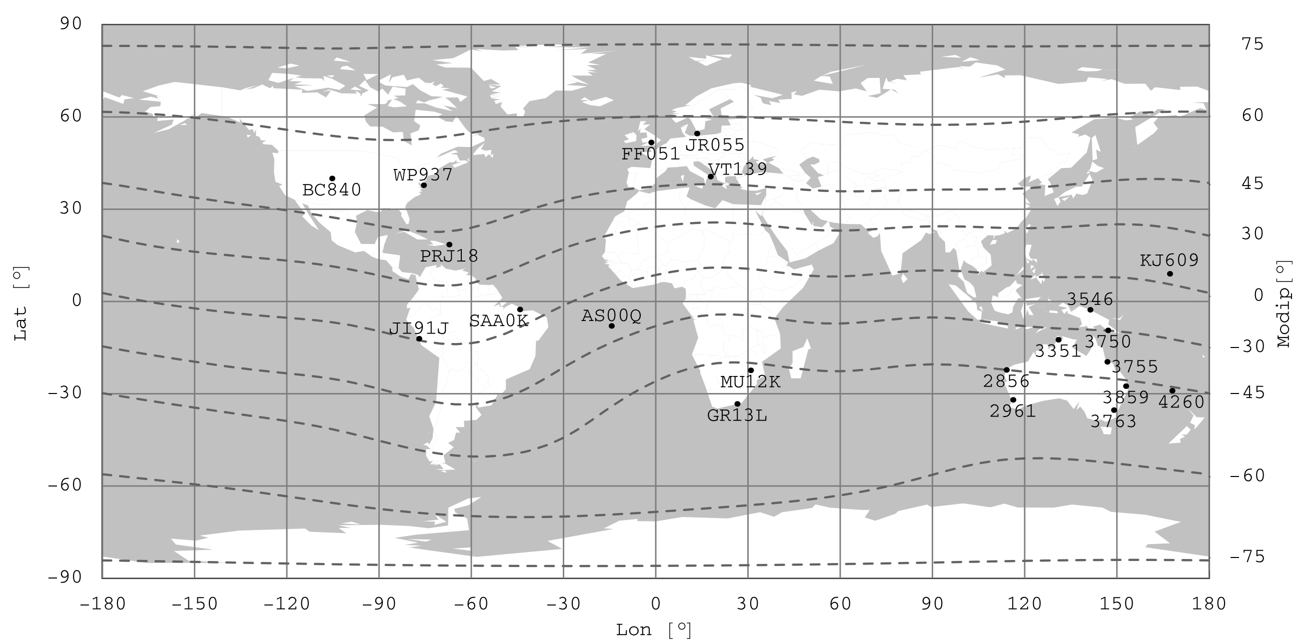

Figure 2. Location of the Ionosondes used for the validation with September 2006 data; modip isolines (dashed) are also indicated.

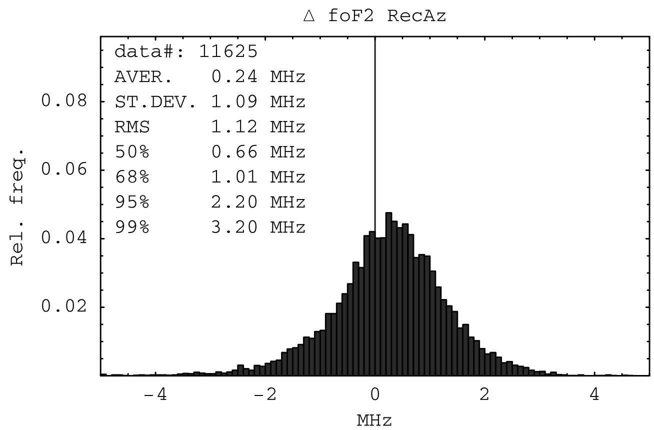

Figure 3. NeQuick 2 driven by Az computed using the vertical TEC map ingestion method: distribution of the differences between modeled and experimental foF2 data for about 20 ionosondes; April 2000. Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are also indicated.

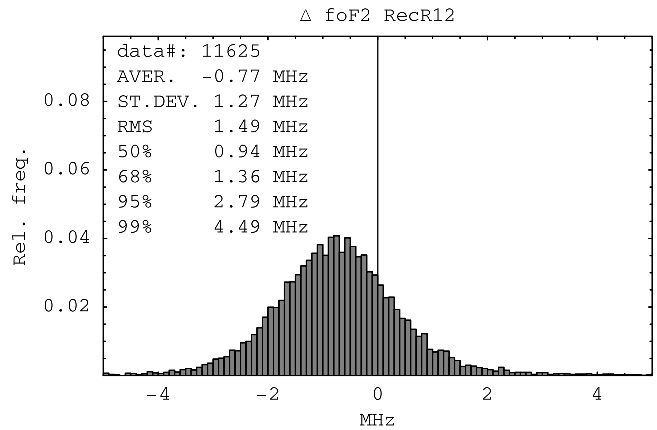

Figure 5. NeQuick 2 driven by R12: distribution of the differences between modeled and experimental foF2 data for about 20 ionosondes; April 2000. Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are also indicated.

NeQuick being adapted to the experimental vertical TEC maps and therefore driven by the effective parameter Az), in Figure 4 (in the case of NeQuick being driven by the daily F10.7) and in Figure 5 (in the case of NeQuick being driven by the R12). As can be seen from the relevant plots, when experimental vertical TEC data are ingested into the model, the capability of NeQuick 2 in reconstructing the critical frequency of the F2 layer is improved if compared with results obtained by the model when it is used in a standard way (namely using the daily solar flux or the monthly mean Sun Spot Number). The improvement, that can be summarized by the reduction of the RMS of the foF2 differences from 1.49 (or 1.46) to 1.12 MHz, is also evident in terms of maximum error since the 99 percentile of the absolute value of the foF2 differences is reduced from 4.49 (or 4.35) to 3.20 MHz. The same analysis has been performed for the data related to September 2006. In addition the same kind of statistics has been carried out separating the low-latitude data (obtained from ionosondes having a modip between −30° and 30°) from the remaining ones. A global overview of the results can be seen in Tables 1 and 2. From these statistics it is possible to state that the general trend observed in the case of all ionosondes, April 2000, is also observed for the mid and low-latitude ionosondes alone and for all the corresponding cases in September 2006. The results presented in this section allow us to quantify the effectiveness of the ingestion technique based on the vertical TEC map ingestion into NeQuick 2. They also display a general weakness of the NeQuick 2 in terms of slab thickness formulation. The slab thickness τ is defined as the ratio of the TEC to the maximum electron density. In terms of foF2 it can be written $\tau = 806.4\ \mathrm{TEC}/foF2^2$ where τ is in km, TEC in TECU (1 TECU = 10^{16} m^{-2}) and foF2 in MHz. The proposed ingestion technique implies that the model vertical TEC has to "match" the experimental vertical TEC at any given location and time. Therefore when the retrieved foF2 are different from the ground-truth values it can be said that

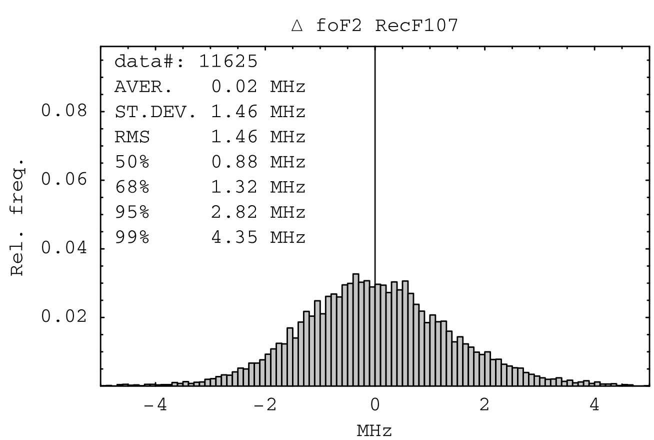

Figure 4. NeQuick 2 driven by F10.7: distribution of the differences between modeled and experimental foF2 data for about 20 ionosondes; April 2000. Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are also indicated.

Table 1. April 2000: Statistics of the Differences Between Modeled and Experimental foF2 Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 11625			Mid Lat, Data 9556			Low Lat, Data 2069		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.24	0.02	−0.77	0.23	0.04	−0.71	0.26	−0.05	−1.06
St dev	1.09	1.46	1.27	0.90	1.34	1.10	1.74	1.92	1.86
RMS	1.12	1.46	1.49	0.93	1.34	1.31	1.76	1.92	2.14
50%	0.66	0.88	0.94	0.60	0.84	0.89	1.20	1.18	1.17
68%	1.01	1.32	1.36	0.90	1.25	1.30	1.70	1.78	1.74
95%	2.20	2.82	2.79	1.82	2.61	2.53	3.19	3.77	4.49
99%	3.20	4.35	4.49	2.52	3.82	3.49	5.22	6.16	7.47

[a]Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are indicated for the NeQuick 2 driven by Az, F10.7 and R12.

Table 2. September 2006: Statistics of the Differences Between Modeled and Experimental foF2 Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 12207			Mid Lat, Data 8814			Low Lat, Data 3393		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.20	0.17	0.05	0.15	0.03	−0.08	0.35	0.52	0.38
St dev	0.73	0.85	0.83	0.57	0.69	0.67	1.03	1.1	1.08
RMS	0.76	0.87	0.83	0.59	0.69	0.68	1.09	1.22	1.15
50%	0.46	0.50	0.48	0.40	0.43	0.42	0.74	0.80	0.73
68%	0.68	0.76	0.74	0.58	0.63	0.63	1.11	1.19	1.11
95%	1.57	1.81	1.73	1.16	1.37	1.35	2.05	2.44	2.27
99%	2.16	2.67	2.49	1.57	1.98	1.93	2.78	3.12	3.05

[a]Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are indicated for the NeQuick 2 driven by Az, F10.7 and R12.

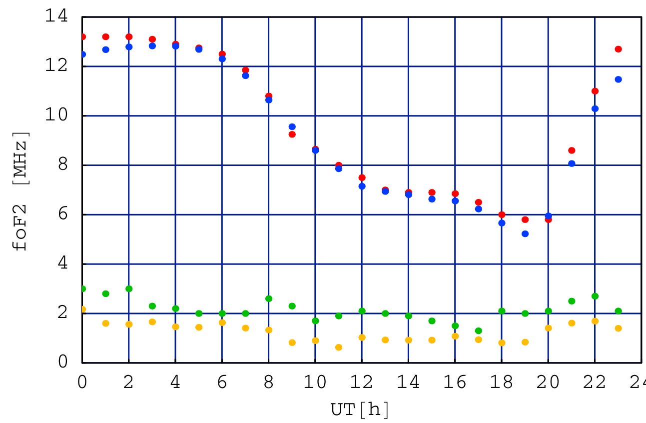

Figure 6. Experimental (red), modeled (blue) foF2 median, experimental foF2 IDW (green) and IDW of (experimental - modeled) foF2 (yellow) as a function of UT for Canberra (3763) ionosonde, April 2000. The modeled values have been obtained with NeQuick 2 driven by Az.

NeQuick2 is not able to perfectly reproduce the experimental slab thickness. The average values in the Az columns of Tables 1 and 2 indicate that in general the NeQuick 2 model slightly underestimates the ionospheric slab thickness.

3.2.2. Using foF2 Median and IDW

[15] In order to better understand the NeQuick 2 capabilities to improve the "weather" description of the ionosphere electron density after vertical TEC maps are ingested, the criteria expressed by *Decker and McNamara* [2007] have been applied. Remembering that an error is the difference between a model-retrieved value and the corresponding experimental observation, we quote that by an ideal climatological model we mean one that performs as well as one that uses the median of the data as the predictor. In that case, the standard deviation of the data would be the climatological Root Mean Square (RMS) error, and the Inter Decile Width (IDW) of the error would be the IDW of the observations. In the present work, we have focussed our attention on the foF2 median and IDW statistics. The median has been used because we had to verify that the vertical TEC map ingestion procedure did not introduce any significant error into the NeQuick 2 retrieved foF2 values. The IDW has been used because the primary goal of ingesting experimental TEC data is to allow the "climatological" model to capture the day-to-day ionospheric variability, i.e., to capture the shorter time scales that characterize the ionospheric "weather". If the ingestion scheme does not lead to noticeable foF2 median errors, this means that the model is still behaving as a good climatological model. Nevertheless, to state that NeQuick 2 (after the data ingestion) is able to track the foF2 day-to-day variability, the model errors must be less than the range of the observations. Therefore comparing the IDW of the model errors with the IDW of the observations allows us to quantify how well the day-to-day variability is being modeled by the NeQuick [*Decker and McNamara*, 2007].

[16] As an example, in Figure 6 the experimental and the NeQuick 2 derived (after the TEC data ingestion) foF2 medians are illustrated together with the foF2 IDW and IDW errors for Canberra (3763) ionosonde, April 2000. From the relevant plot it is possible to see that the median values have an error up to about 1 MHz, but the IDW errors are usually well below the corresponding experimental IDW. This indicates that the ingestion scheme allows NeQuick 2 to capture the day-to-day foF2 variability. For completeness these plots have been produced for all the ionosondes available, also considering the cases where F10.7 and R12 have been used to calculate the relevant foF2 model data and consequently the IDW errors. Due to the large amount of data, to analyze the foF2 medians, the foF2 IDW and IDW errors, a statistical approach based on relative frequency distribution has been adopted. As in the case of single foF2 data analysis the results have been separated in accordance to the solar activity period and the modip of the stations. A global overview of the results concerning the median foF2 values is given in terms of the relative frequency distribution of the difference between the modeled and the experimental foF2 median values (the foF2 median error). The statistics are summarized in Tables 3 and 4 for the month of April 2000 and September 2006 respectively. It is understood that the columns Az, F107, R12 indicate that the foF2 median errors have been computed using the NeQuick 2 model driven by Az, F10.7 and R12 respectively. As expected, the performances of NeQuick 2 (after the data ingestion is performed) in terms of median values are not always improved

Table 3. April 2000: Statistics of the Differences Between Modeled and Experimental foF2 Median Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 488			Mid Lat, Data 395			Low Lat, Data 93		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.17	−0.12	−0.83	0.16	−0.11	−0.78	0.22	−0.16	−1.07
St dev	0.89	0.76	0.82	0.68	0.55	0.55	1.48	1.32	1.48
RMS	0.91	0.77	1.17	0.70	0.56	0.95	1.49	1.32	1.81
50%	0.53	0.44	0.83	0.47	0.39	0.81	1.05	0.78	0.94
68%	0.81	0.61	1.05	0.72	0.54	1.01	1.45	1.00	1.44
95%	1.71	1.32	1.84	1.31	1.12	1.60	N/A	N/A	N/A
99%	2.44	2.84	4.26	1.87	1.65	2.18	N/A	N/A	N/A

[a]Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are indicated for the NeQuick 2 driven by Az, F10.7 and R12.

Table 4. September 2006: Statistics of the Differences Between Modeled and Experimental foF2 Median Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 460			Mid Lat, Data 328			Low Lat, Data 132		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.20	0.17	0.06	0.14	0.02	−0.07	0.35	0.53	0.39
St dev	0.54	0.58	0.57	0.41	0.42	0.41	0.75	0.73	0.76
RMS	0.57	0.60	0.58	0.43	0.42	0.42	0.82	0.90	0.85
50%	0.33	0.34	0.33	0.30	0.28	0.29	0.59	0.62	0.56
68%	0.49	0.51	0.49	0.40	0.39	0.41	0.86	0.87	0.86
95%	1.21	1.22	1.13	0.84	0.86	0.80	1.63	1.80	1.66
99%	1.66	1.96	1.79	1.17	1.17	1.07	1.77	2.35	2.22

[a]Average, standard deviation and RMS of the differences and 50, 68, 95, 99 percentiles of the absolute values of the differences are indicated for the NeQuick 2 driven by Az, F10.7 and R12.

Table 6. September 2006: Statistics of the Ratio [IDW of NeQuick 2 Errors]/[IDW of Experimental foF2] Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 460		Mid Lat, Data 328		Low Lat, Data 132	
	Az	F107	Az	F107	Az	F107
Aver	0.82	1.05	0.78	1.05	0.92	1.05
St dev	0.21	0.17	0.18	0.18	0.23	0.15
RMS	0.85	1.07	0.80	1.07	0.95	1.06
50%	0.80	1.03	0.77	1.02	0.89	1.04
68%	0.88	1.11	0.85	1.11	0.98	1.12
95%	1.22	1.38	1.13	1.39	1.36	1.35
99%	1.44	1.51	1.26	1.52	1.48	1.42

[a]Average, standard deviation, RMS and 50, 68, 95, 99 percentiles of the ratio are indicated for the NeQuick 2 driven by Az and F10.7.

as far as the RMS of the differences is concerned. A slight worsening with respect to the NeQuick driven by the flux of the day is also visible (e.g. in Table 3, considering all latitude data, the RMS are 0.77 and 0.91 MHz if the NeQuick is driven by F10.7 or Az respectively).

[17] Tables 5 and 6 give a global overview of the results concerning the IDW of the foF2 values and errors in terms of the relative frequency distribution of the ratio: [IDW of NeQuick errors]/[IDW of experimental foF2]. The reason is that the capability of a model to capture the foF2 day-to-day variability at a given UT is visualized by the IDW of the model errors being smaller than the IDW of the observations. A ratio less than 1 indicates a performance better than an ideal climatological model that uses the median of the data as the predictor. The statistics are summarized in Tables 5 and 6 for the month of April 2000 and September 2006 respectively. As in the previous case, the columns Az and F107 indicate that the IDW of NeQuick errors have been computed using the NeQuick 2 driven by Az and F10.7 respectively. The column corresponding to the NeQuick 2 driven by the R12 has not been considered because the ratio is always equal to 1. The explanation is that a ratio of 1 indicates the performance of an ideal climatological model that uses the median of the data as the predictor or, more generally, a constant foF2 value for the given UT in the given month. Also, NeQuick for a given month at a given location and for a given UT, always gives the same foF2 value if the same solar activity index is input. As can be seen from the statistics (column Az) indicated in Tables 5 and 6, the vertical TEC map ingestion procedure on average (0.68 for April 2000 and 0.82 for September 2006) allows the NeQuick 2 to perform better than an ideal climatological model. The better performance is obtained during high solar activity regardless of the station latitude. On the contrary, considering the F107 columns, it can be seen that NeQuick 2 driven by the daily solar flux is not able to perform better than an ideal climatological model. This is indicated for example by the average value of the [IDW errors]/[IDW foF2] ratio of 1.35 and 1.05 at all latitudes for high and low solar activity.

Table 5. April 2000: Statistics of the Ratio [IDW of NeQuick 2 Errors]/[IDW of Experimental foF2] Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 488		Mid Lat, Data 395		Low Lat, Data 93	
	Az	F107	Az	F107	Az	F107
Aver	0.68	1.35	0.64	1.36	0.82	1.30
St dev	0.26	0.41	0.26	0.42	0.19	0.37
RMS	0.72	1.41	0.69	1.42	0.84	1.35
50%	0.64	1.28	0.59	1.29	0.81	1.24
68%	0.75	1.42	0.68	1.42	0.90	1.40
95%	1.05	2.03	1.03	2.05	N/A	N/A
99%	1.79	3.14	1.81	3.17	N/A	N/A

[a]Average, standard deviation, RMS and 50, 68, 95, 99 percentiles of the ratio are indicated for the NeQuick 2 driven by Az and F10.7.

[18] In summary, it is possible to state that the data ingestion procedure described in 3.1 in general allows the NeQuick 2 to represent the ionospheric foF2 "climate" (Tables 3 and 4) in a sufficiently accurate way since the model performance after the data ingestion is not degraded if compared to that of the model itself when used in a standard (climatological) way. In fact, the data ingestion procedure improves the model performance in reproducing the ionospheric "weather" in terms of foF2 day-to-day variability on a global geographical scale because after the data ingestion, the NeQuick 2 performs better than an ideal climatological model and better than the model itself when it is driven by the daily solar flux (Tables 5 and 6). Nevertheless, there is still the need to improve the NeQuick 2 accuracy in terms of slab thickness formulation (Tables 1 and 2).

4. RO-Derived TEC Data Ingestion

[19] The most sophisticated assimilation models are able to ingest RO-derived TEC data [e.g., *Komjathy et al.*, 2010; *Angling*, 2008; *Scherliess et al.*, 2006] in order to improve the 3D reconstruction of the ionosphere electron density. Indeed there are simpler methods that can be applied to GPS occultation data to retrieve electron density profiles in the ionosphere. One of these is the Abel inversion [e.g., *Schreiner et al.* 1999], an algorithm relatively easy to be implemented that implies the assumption of spherical symmetry for the ionospheric electron density. As it is well known, this assumption could lead to wrong electron density estimates, especially at lower ionospheric heights. A lot of

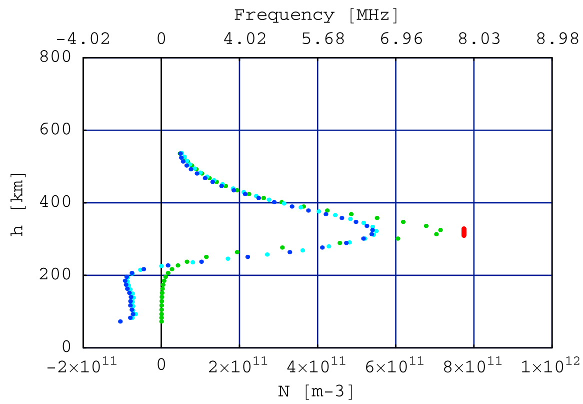

Figure 7. Vertical electron density profiles: onion peeling (blue), CDAAC (light blue), NeQuick 2 adapted to RO-derived TEC data (green); the red line represents the experimental peak density as measured by Kwajalein (KJ609) ionosonde; 21 September 2006, 0900 UT.

effort has been expended to mitigate the effects of the spherical symmetry assumption and in general the best results have been obtained in the cases when additional ionospheric data, like for example ground-based TEC data, have been used [*Hernández-Pajares et al.*, 2000]. Taking into account this background and always considering the needs of simplicity and speed for the model, a method to ingest only RO-derived TEC data into NeQuick 2 has been developed using the concept of multiple effective parameters. For this purpose the model source code has been extensively modified to accept as inputs two effective parameters related to the original F10.7 and a coefficient used to modulate the thickness parameter of the NeQuick 2 bottomside profile.

[20] In the following section the first results obtained by ingesting data from the Constellation Observing System for Meteorology Ionosphere and Climate (FORMOSAT-3/COSMIC; http://www.cosmic.ucar.edu/) will be presented.

4.1. The Ingestion Technique

[21] At a given epoch, an occultation event is considered and all the relevant data like the TEC along the Low Earth Orbiter (LEO)-to-GPS satellite link below the LEO orbit are supposed to be known. The "onion peeling" algorithm [e.g., *Leitinger et al.*, 1997], is applied to retrieve a "vertical" electron density profile in the ionosphere from the TEC values calibrated using the concept of auxiliary data as indicated by *Schreiner et al.* [1999]. From the onion peeling derived profile the height of the maximum electron density is considered. Taking advantage of the ITU-R coefficients (formerly CCIR [*Comité Consultatif International des Radiocommunications*, 1967]) and of the Dudeney formula [*Dudeney*, 1983], already implemented into NeQuick 2 to compute foF2, M(3000)F2 and hmF2, an effective parameter is computed minimizing the difference between the RO-derived and the NeQuick 2-derived hmF2 as function of (formally) F10.7. This parameter, (symbol Az_hmF2) is the effective ionization level value that allows NeQuick 2 to reproduce the RO-derived "experimental" hmF2. Using the NeQuick 2 driven by the Az_hmF2, the RMS of the RO-derived TEC mismodelings is minimized as a function of an F2 bottomside thickness parameter "correcting factor", and F10.7 (that in this case acts only on the part of the model devoted to the calculation of the electron density peak values). In this way, an additional two effective parameters are defined: the correcting factor B2bot_mod, that is essentially used to constrain the model slab thickness and Az_foF2, that determines the peak electron density values of the NeQuick for the area of interest. The effective parameters and the correcting factor can therefore be input into NeQuick 2 in order to (locally) estimate the 3D electron density of the ionosphere for the epoch considered.

[22] The use of the effective parameters Az_foF2 and Az_hmF2 is required to estimate foF2 and hmF2 values with the ITU-R coefficients all over the region of the occultation event. In this way the model peak parameters can be estimated for all the points needed for the TEC calculation along the LEO-to-GPS link below the LEO orbit.

4.2. The Ingestion Technique Validation

[23] Due to the recent development of the technique and the considerable amount of calculation required, a first validation of the proposed method to ingest RO-derived TEC data in the NeQuick 2 model has been carried out considering only one day of data: September 21th 2006. As usual, the validation has been based on the comparison between the model retrieved and the corresponding ionosonde-measured foF2 values. In the present case, the model retrieved foF2 data have been obtained after ingesting RO-derived TEC data into NeQuick 2 as indicated in 4.1. The RO data used for the model adaptation have been downloaded from the COSMIC Data Analysis and Archive Centre (CDAAC; http://cosmic-io.cosmic.ucar.edu/cdaac/index.html). In particular, the so called ionPhs files, containing Ionospheric excess phases, have been processed to obtain the relevant electron density profiles (after the application of the onion peeling algorithm) and all the other necessary data for the ingestion like the calibrated TEC values along the LEO-to-GPS link below the LEO orbit.

[24] After inverting one day of RO data with the onion peeling algorithm, the coordinates and the epoch of occurrence of the electron density peaks have been considered. The RO data corresponding to profiles having the peak density co-located with some ionosonde measurement have been ingested in NeQuick 2. The co-location criteria have been defined as follows: the difference in latitude and longitude between the RO-derived peak density and the ionosonde location have been requested to be less than 2° and 4° respectively, while the difference in time interval between the RO-derived peak density and the ionosonde measurement has been requested to be smaller than 15 minutes. Due to the co-location criteria adopted a very limited amount of RO data has been left for the validation of the ingestion technique. Therefore a statistical analysis of the foF2 errors has not been done. Nevertheless it can be said that the capabilities of the proposed ingestion technique of reconstructing the critical frequency of the F2 layer are usually comparable to those of the onion peeling algorithm. In some specific cases the approach described in 4.1 is able to perform better than the Abel inversion. As an example in Figure 7 the electron density profiles obtained from RO data applying the onion peeling algorithm (blue) and the ingestion scheme based on the NeQuick 2 adaptation

to RO-derived TEC data (green) are plotted together with the experimental value of the peak density as measured by the Kwajalein (KJ609) ionosonde. The electron density profile obtained by CDAAC (ionPrf file) has been added in light blue for comparison purposes. Even if from the cases analyzed the proposed ingestion method seems to be promising, additional studies are needed to fully validate this procedure based on the RO data ingestion in NeQuick 2.

5. Conclusions

[25] The data ingestion procedure based on the vertical TEC map ingestion in NeQuick 2 in general allows the model to adequately represent the ionospheric foF2 "climatology" because the model performance after the data ingestion is not degraded if compared to those of the model itself when used in a standard way. The data ingestion procedure improves the model performance in reproducing the ionospheric "weather" in terms of foF2 day-to-day variability on a global geographical scale because after the data ingestion the NeQuick 2 performs better than an ideal climatological model that uses the median of the data as the predictor. Nevertheless, there is still the need to improve the NeQuick 2 formulation in terms of slab thickness. The data ingestion scheme relying on the NeQuick 2 adaptation to RO data seems to be promising, but additional studies are needed for a complete validation, considering that a full assimilation scheme is needed to allow the NeQuick to ingest different kinds of data.

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